ADVANCED POWER & ENERGY PROGRAM
UNIVERSITY of CALIFORNIA · IRVINE

Integrating Clean Energy Technologies with Existing Infrastructure

Western Energy Hub Site Benefits for Rapid Clean Regional Grid Transition

AUTHORS:

Jeffrey Reed, Ph.D.
Chief Scientist, Renewable Fuels and Energy Storage, Advanced Power and Energy Program

Jack Brouwer, Ph.D.
Associate Director, Advanced Power and Energy Program
Director, National Fuel Cell Research Center

Robert Webster
Co-Founder & Chief Strategy Officer, Magnum Development

www.apep.uci.edu

Contents

www.apep.uci.edu
Phone 949-824-1999

University of California, Irvine
Engineering Laboratory Facility
Irvine, California 92697-3550

Executive Summary

The UC Irvine Advanced Power and Energy Program, with technical input from Magnum Development, has developed this white paper to describe how the Western Energy Hub ("WEH") site, located adjacent to the Intermountain Power Project ("IPP") in Millard County, Utah, can serve as a foundation of the ***Sustainable City pLAn*** for Los Angeles, Southern California, and the Western region.

This regional platform, with ready access to Southern California energy and transportation markets, offers a unique combination of geography, geology, energy and transportation infrastructure, and renewable energy resources that can serve to rapidly deploy new clean energy technologies and practices at commercial scale—meeting regional needs and speeding clean energy adoption and use worldwide. This white paper builds upon a strong foundation of clean and sustainable energy research and development at UCI APEP.[1]

Foundation of the Regional Green Energy Transition

The European Union energy and transportation vision foresees hydrogen fulfilling roughly 20% of primary energy demand in transportation and industry, as well as energy functions not easily served by other sources (such as zero-emission heavy-duty transportation, goods movement, aviation, and certain industrial and chemical demands)—and the hydrogen will be derived predominantly from renewable electricity. Hydrogen is integral to the zero-carbon, zero-pollutant mix because its high energy density, transportability, and ability to store and retain energy across days, months and even years provides functionality and scale that are not reachable through other approaches.

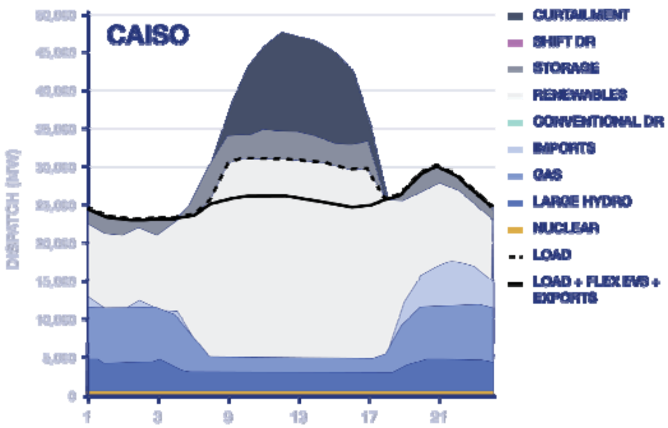
Similarly, Los Angeles Mayor Eric Garcetti's bold ***Sustainable City pLAn*** properly places renewable electricity and supporting energy storage as the foundation for the energy future of Los Angeles and the Southern California region. Renewable hydrogen is perhaps nature's best zero-carbon energy carrier and can provide energy storage at massive scale as a foundation of the long-term vision of zero-carbon and zero-pollutant emissions. Los Angeles can join the growing list of global clean-energy leaders that includes the European Union, Japan, Australia, South Korea, China, and major multi-national companies in embracing hydrogen as a pillar of a clean energy and transportation future.

A key challenge to relying heavily on solar and wind power is that these sources cannot be ramped up and down to serve demand as it varies over the course of a day, across days, and even from season to season. Solar energy is not generated at all during the nighttime, and wind energy profiles vary significantly and do not match load patterns. When renewable energy comprises over 60% of the

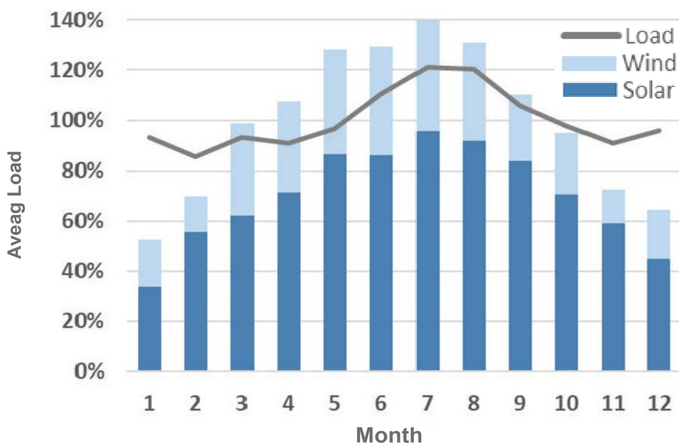
1 For example: (a) Maton, et al., "Dynamic modeling of compressed gas energy storage to complement renewable wind power intermittency," *International Journal of Hydrogen Energy*, 38, 7867-7880, 2013; (b) Saeedmanesh, et al., "Hydrogen is essential for sustainability," *Current Opinion in Electrochemistry*, 12, 166-181, 2018; (c) Colbertaldo, et al., "Impact of hydrogen energy storage on California electric power system: Towards 100% renewable electricity," *International Journal of Hydrogen Energy*, 44, 9558-9576, 2019.

electricity mix, resource planning models predict that energy production will exceed demand in over 20% of the hours of the year, totaling between 5% and 10% of all renewable power produced. The figure below depicts a representative September day with renewables supplying 60% of the energy. Note the magnitude of excess renewable power in the middle of the day, even after deploying 3.0 gigawatts (GW) of short-duration storage (purple band) and activating all available flexible electric vehicle charging (dashed line).

Excess Renewable Power Production on a High-Solar Day in 2030



Source: RESOLVE Case 42mmt_Ref_20180416_2017_IEPR. https://www.cpuc.ca.gov/General.aspx?id=6442457210



Source: UC Irvine

Renewable energy production is at its minimum during the winter and peaks during the summer when both wind and solar production are high. The energy produced in the lowest-production month is only about one-third that of the highest-production month. Addressing this seasonal imbalance will require 10s of GW-scale storage resources capable of storing hundreds of thousands of MWh of power over monthly time scales with minimal losses. The long duration and seasonal storage challenges become exponentially more difficult as Los Angeles and the state of California move toward achieving their respective goals for 100% clean energy conversion. Geological gas storage is the only technically proven solution for these grid services, while at the same time renewable hydrogen may be the ideal fuel to deliver completely zero emissions in many sectors.

Western Energy Hub – Renewable Energy Development Complex

A recent *Science* article (Davis et al., 2018) notes that many essential energy services, aviation, long-distance transport and shipping, ammonia production, steel and cement manufacturing, and long-duration storage for a 100% renewable electric grid (see illustration on the next page) cannot be accommodated without the use of resources that can produce, store, transmit, and distribute renewable energy and convert it back to electricity with zero emissions when needed. Renewable hydrogen is uniquely suited to serve this role. The IPP uniquely meets these criteria. It is situated above the only known “Gulf Coast”-style, utility-scale salt dome in the western United States. WEH’s salt caverns, which lie 3,000 feet below the surface, can store a variety of gases and liquids that can economically and efficiently be drawn upon to meet variable power requirements, including:

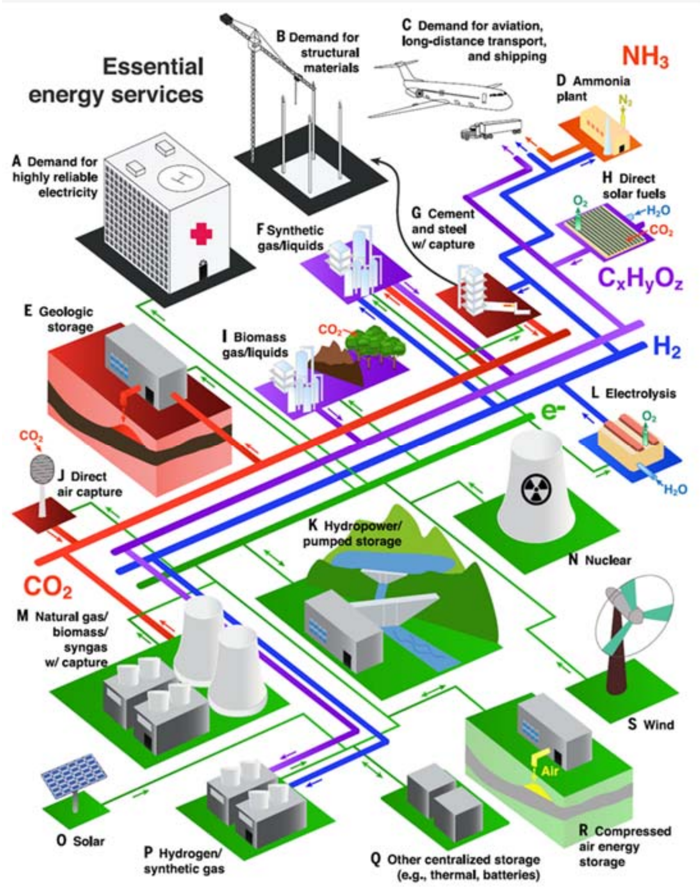
- **Green hydrogen**

A renewable fuel which can be produced by using excess renewable energy to electrolyze water and later be drawn upon to meet peak demand or, alternatively, distributed to end markets for use in manufacturing, industry, or as a transportation fuel.

- **Compressed air for energy storage**

A technology that enables bulk energy storage by converting off-peak power from green sources (wind and solar) into compressed air that can be released to produce electric power through a gas turbine at any time.

The Future Energy and Transportation Ecosystem

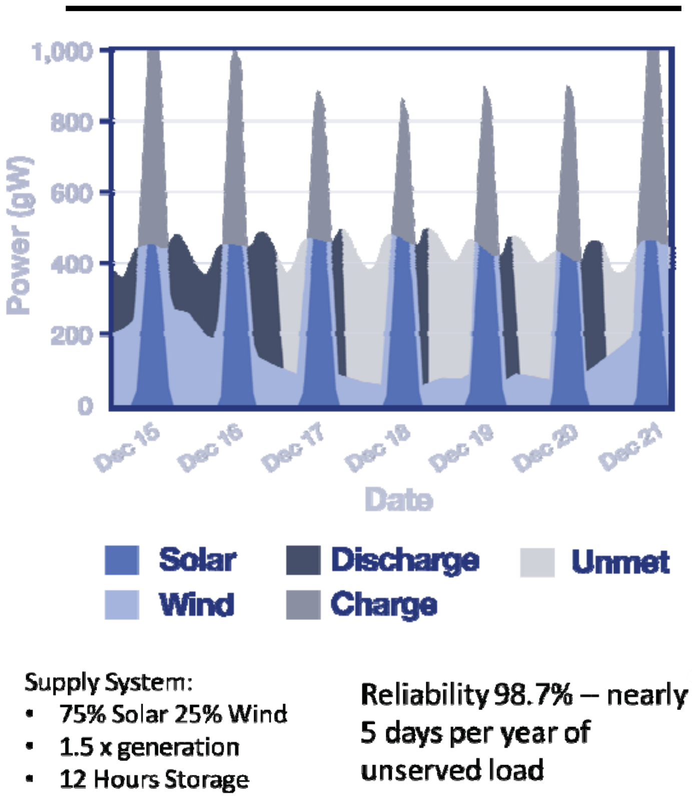


Source: From Davis, et al., Science **360**, *1419 (2018)*

Built as a coal-fueled power plant in Delta, Utah, in the 1980s, IPP's owner, the Intermountain Power Agency (IPA), is now in the process of converting the plant's baseload resources to combined-cycle units fired with a blend of natural gas and renewable hydrogen that can support loads when intermittent energy resources are insufficient to meet demand. This repowering plan will assist utilities in IPA's downstream markets in meeting the growing demands of state initiatives seeking to reach high fractions of renewable energy in their generation portfolios.

WEH's Millard County, Utah, site sits amid a wide range of existing and planned/permitted infrastructure—high-voltage transmission lines, natural gas and refined product pipelines, railroads, and interstate highways—that will facilitate the storage, conversion, and conveyance of upstream green energy resources to downstream markets in the western United States.

Because WEH sits immediately adjacent to IPP, it provides an economical solution to western renewable "over generation," reducing the potential for curtailment by permitting renewable electricity to be stored during periods of excess generation and released when large increments of dispatchable generation are required to meet utility load service and reliability requirements. As a "shock absorber" for the regional grid, its storage capability will enhance grid reliability and efficiency through optimization of existing transmission line loads and defer the need to build new transmission assets.



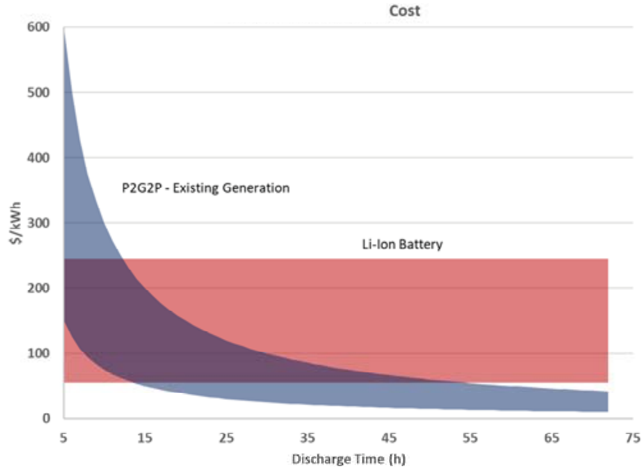
Source: Shanner, et al., 2018

Without such large-scale, long-duration storage and distribution infrastructure, a 100% zero-carbon energy system dominated by solar and wind energy cannot reliably meet projected energy requirements. A recent study shows that, even with a 50% overbuild (capacity above what is needed to meet annual energy requirements, on average), and including 12 hours of battery energy storage to meet the entire demand, the system would be unable to meet electricity demands for more than 100 hours of the year. Stated differently, the grid would face outages roughly 20 times more often (or longer) than current levels.[2]

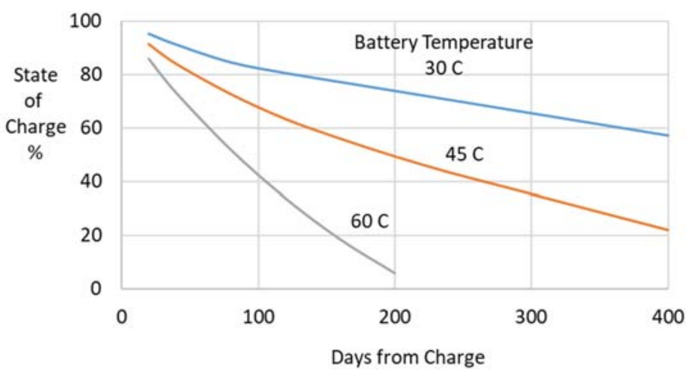
Storage of efficient and clean energy carriers such as hydrogen and compressed air can provide a scalable platform to address these issues, serving the same function for renewable energy as natural gas storage serves for conventional power generation today. This is not the only solution, but rather a key pillar of an optimized portfolio that includes lithium-ion and other types of batteries for short-duration energy storage applications and pumped hydro (where and when available) and other solutions working synergistically for medium- and long-duration storage.

2 U.S. Energy Information Administration (EIA), U.S. Department of Energy, "Average frequency and duration of electric distribution outages vary by states," April 5, 2018, available on-line at: https://www.eia.gov/todayinenergy/detail.php?id=35652

Storage System Capital Cost

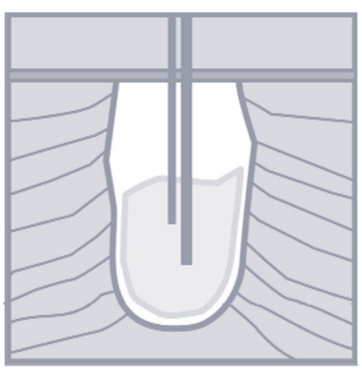


Lithium-ion Battery Self Discharge



Source: UCI APEP from data in Redondo-Iglesias, et al., *Global Model for Self-Discharge and Capacity Fade in Lithium-Ion Batteries Based on the Generalized Eyring Relationship*, IEEE Transactions on Vehicular Technology, Vol. 67, No. 1, January 2018, pp. 104—113.

Salt Caverns



Lithium-ion batteries are the most ubiquitous energy storage technology today. However, they face two challenges in storage applications requiring more than a few hours of storage and/or requiring energy to be stored over long periods of time (weeks to months). The first is cost. Energy storage system cost is driven by both the maximum rate of charge and discharge (measured in megawatts) and by the amount of energy stored (measured in megawatt-hours). The cost of batteries increases in direct proportion to both and, in particular, battery cost increases directly with the quantity of energy stored.

Secondly, battery systems lose their charge over time through the phenomenon of self-discharge[3] as shown in the figure below left. As a result, battery energy storage systems are not well-suited for storing energy for extended periods of time (as most consumers will likely be aware from their experience with automotive and personal electronics batteries, which lose their charge over long periods of non-use).

SALT-CAVERN GEOLOGICAL STORAGE

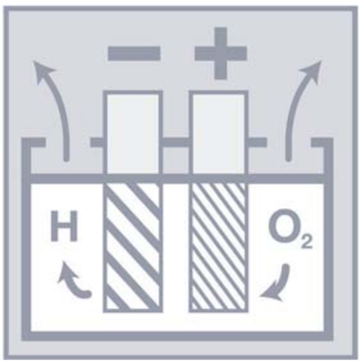
Geological storage such as that available at WEH's salt caverns, by contrast, is the most cost-effective approach for storing large amounts of energy because of the separate scaling of power (size of electrolyzer and fuel cell) and energy (size of storage resource) and massive size (each cavern can be individually sized to store between 2 million and 40 million cubic feet of natural gas, compressed air, or liquid energy product). Geological storage has a very low cost per unit of stored energy in comparison to other forms of energy storage. And unlike battery storage systems, geological storage systems incur a cost to provide a given rate of charge or discharge (rate) but incur very little additional cost for storing more energy (quantity).

Long-term storage of hydrogen in geological formations is fully proven. Two large salt-cavern hydrogen storage facilities in Texas, operated by Praxair[4] and Air Liquide[5], are interconnected with

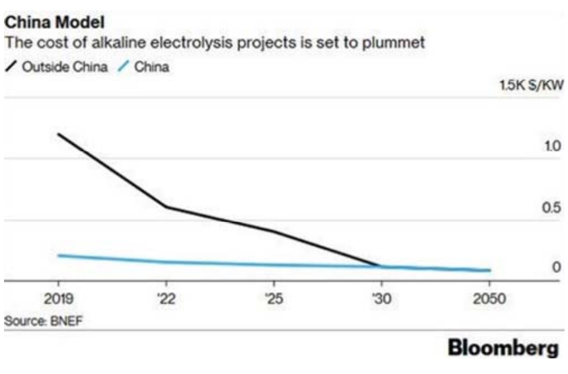
3 Redondo-Iglesias, et al., "Global model for self-discharge and capacity fade in lithium-ion batteries based on the generalized Eyring relationship," *IEEE Transactions on Vehicular Technology*, Vol. 67, No. 1, 2018.
4 U.S. Patent # US9284120B2, Methods for storing hydrogen in a salt cavern with a permeation barrier, Praxair Technology Incorporated, 2014.
5 Air Liquide, "Air Liquide operates the world's largest hydrogen storage facility," January 3, 2017, available on-line at: https://en.media.airliquide.com/news/usa-air-liquide-operates-the-worlds-largest-hydrogen-storage-facility-edf8-56033.html

a vast hydrogen pipeline network. Stored hydrogen can be returned to the grid as electricity in a variety of ways, including for use as a blend stock for existing natural gas combined-cycle power plants, or in fuel cells or turbines running on pure hydrogen or mixtures of hydrogen with natural gas. Beyond its storage function, hydrogen can also be transported to demand areas for use as a zero-emission vehicle fuel. This "sector coupling" allows hydrogen to be optimally dispatched for use as fuel for electricity generation or as vehicle fuel based on demand and price dynamics.

Electrolyzer Installation



Electrolysis Cost Forecast to "Plummet"



Reference: Hydrogen's Plunging Price Boosts Role as Climate Solution By Will Mathis and James Thornhill August 21, 2019, 12:11 AM MDT

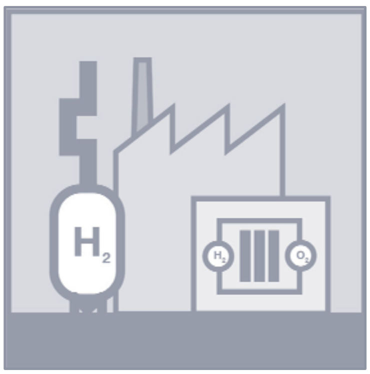
ELECTROLYZERS/ POWER-TO-GAS

Electrolyzers, which use electrical energy to split water into hydrogen and oxygen, consume no more water than a thermal power plant of similar rating, create no pollution, are very quiet, and have a small, low-profile footprint. When the input electricity is from renewable resources, the electrolytic hydrogen produced is a fully renewable, carbon-free fuel. Electrolyzers can ramp up and down to follow grid conditions such as available supply (or oversupply) of renewable electricity and provide ancillary services to address local frequency and voltage fluctuations and congestion on the grid.

Electrolyzers serve two primary functions. First, they can act as large-scale bulk electric storage devices by producing hydrogen for later use as fuel for power generation to return electric energy to the grid when desired. Because hydrogen can be stored over long periods of time without loss of energy, hydrogen energy storage can serve sub-hourly to seasonal storage time scales. Second, the produced hydrogen can be used for other applications, principally transportation fuel, but also refining, fertilizer production, process feedstock, high-temperature heat, and other industrial and chemical processes. Producing hydrogen for these applications by deploying electrolyzers as flexible electric loads can serve the same grid energy storage functions as electric-to-chemical battery energy storage, but often can do so more economically due to the value of the renewable hydrogen fuel or chemical that is replaced in these non-electric uses of stored grid energy. Recent analysis by Bloomberg (figure to the left) projects dramatically lower costs for electrolyzers as global deployment scales.

California has three electrolytic hydrogen projects under development or in operation. One system is operating at Sunline Transit Agency in Palm Springs and two others are in development with support from the California Energy Commission. Overseas development is further ahead, with over 30 megawatt-scale projects operating in Germany, Japan, England, the Netherlands, and Canada. The demand potential for renewable hydrogen is large. A high-demand scenario for renewable hydrogen in California reaches over 4 million kilograms per year by 2030 and over 4 billion kilograms per year by 2050.[6] For comparison, the 2050 quantity of renewable hydrogen would require over 200 TWh of electric power and over 60 GW of electrolyzer capacity to produce, which is 40% to 65% of projected electrical demand in those years assuming all the hydrogen were to be produced via electrolysis.[7]

Hydrogen



HYDROGEN-POWERED ELECTRIC POWER GENERATION

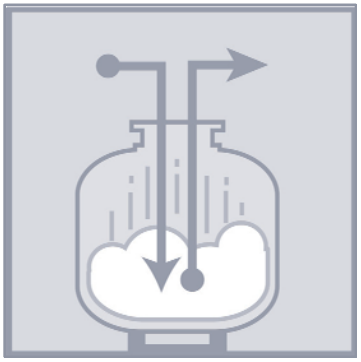
Hydrogen energy storage use cases that return electricity to the grid require electric power generation technologies that can efficiently use hydrogen fuel. Existing combined-cycle power plants have adequate flexibility to blend significant amounts of hydrogen—up to 20%—into their natural gas fuel supply. Conventional engines and turbines can also be designed to run on pure hydrogen. Several companies are developing advanced, highly efficient gas turbines to run on pure hydrogen. These power plants are forecast to achieve over 70% efficiency operating in combination with compressed air energy storage. Advanced natural gas combustion turbines currently planned to enter service at the Intermountain site in 2025 will be capable of co-firing hydrogen at 30% initially, with potential for 100% hydrogen fuel as combustion technologies evolve.

Fuel cells, which produce electricity through a non-combustion, electrochemical process, are also ideally suited for hydrogen-powered electricity generation. They offer high conversion efficiency, produce no criteria pollutant emissions, and have been in commercial deployment for over 20 years with over 300 MW of installed capacity in California alone and over 1,000 MW worldwide. Reversible fuel cells, which are bi-directional electrochemical devices that can use electricity to make hydrogen and also use hydrogen to make electricity, are on the horizon as well.

6 UCI APEP *Renewable Hydrogen Production Roadmap.*

7 Wei, et al., 2019, *Building a Healthier and More Robust Future: 2050 Low-Carbon Energy Scenarios for California*. CEC-500-2019-033.

CAES



COMPRESSED AIR ENERGY STORAGE (CAES)

Compressed air energy storage is a powerful adjunct to bulk storage of hydrogen as an integrated electric energy storage system. Renewable energy can be used to compress air to a high pressure, typically up to around 2,800 pounds per square inch (or 70 times atmospheric pressure), to store electrical energy in the same type of formations as those used for hydrogen storage. The energy in the stored high-pressure air can be recovered through various power cycles.

One of the most efficient approaches is to use the stored air to replace the compressor in a standard gas turbine cycle. To release the stored energy, the compressed air is routed to a gas turbine that can be fueled with a mixture of renewable hydrogen and natural gas to produce electricity when desired. Together, CAES—with renewable hydrogen used for firing the gas turbine upon discharge of the air—can dramatically increase the electrical energy recovery by increasing turbine efficiency to over 70%. Using renewable hydrogen would eliminate greenhouse gas emissions and significantly reduce pollutant emissions.

Worldwide there are currently two compressed air energy storage facilities in operation, one in Huntorf, Germany, and one in McIntosh, Alabama. These technologies are ripe for deployment to serve regional markets and address the energy storage and renewables integration challenges of Los Angeles and the Southern California region at a massive scale.

The Platform

PLATFORM FOR REGIONAL CLEAN ENERGY AND TRANSPORTATION INTEGRATION

A unique combination of resources and infrastructure makes the WEH site an exceptional platform for the development of a regional clean energy hub serving both power and transportation markets. The potential exists to use the massive and unique salt cavern resource to store wind and solar energy in the forms of hydrogen and compressed air and to access greater Los Angeles energy and transportation markets via a 2,400 MW, 500 kV direct-current transmission line, as well as major rail and highway routes for moving hydrogen to regional transportation markets. The scale and breadth of this capability cannot be matched by other solutions, venues, or sets of resources and capabilities. Using the clean power generation and energy storage resources of the WEH will be the key enabling concept for transforming energy and transportation markets to completely zero emissions in Southern California, meeting the policy goals of the ***Sustainable City pLAn*** and SB 100.